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Interactions among Irrigation and Nitrogen Fertility Regimes on Mid-South Cotton Production

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ABSTRACT

To maximize profits, cotton (*Gossypium hirsutum* L.) producers must make the most efficient use of expensive production inputs, such as irrigation and N fertilization. Objectives for this research were to determine how cotton responded to varying levels of irrigation and N fertilization. Field studies were conducted from 2009 to 2012 at Stoneville, MS, using four cotton cultivars. Two soil moisture regimes (dryland and irrigated) and three N fertilization levels (0, 56, and 112 kg N ha^{-1}) were imposed on these varieties. Dry matter partitioning, leaf chlorophyll (Chl) concentration, leaf Chl fluorescence, lint yield, yield components, and fiber quality data were collected on all the plots. All the cotton cultivars responded similarly to N fertilization and irrigation. Although cotton's growth responded to both N and irrigation, the level of the benefit from one of these inputs was dependent on the availability of the other component. The highest N fertility rate had higher leaf Chl levels and Fv/Fm fluorescence ratios. Lint yield did not respond to irrigation when no N had been applied. Similarly the lint yield N response was muted when the soil moisture was limited. These data will allow producers to make more informed irrigation and N input allocation decisions, apparently regardless of the cultivar grown.

Growing cotton in the current economic climate has become a more difficult endeavor for many U.S. cotton producers. Challenges confront producers on lint prices, which many consider not currently competitive with the price offered for maize (*Zea mays* L.) or soybean [*Glycine max* (L.) Merr.]. In addition, costs have risen for many of the inputs required or commonly used in producing a cotton crop. These two forces have made turning an economic profit difficult for many cotton farming enterprises. Although lint prices are ultimately determined by the global marketplace, producers have somewhat more discretion and control when it comes to input decisions. Therefore, producers need as much information as possible to make decisions allowing for more efficient input utilization.

Two cotton production inputs that have experienced recent price increases are irrigation and N fertilization, both of which are closely tied to the price of fossil fuels. Many of the irrigation wells across the cotton production belt are driven by diesel engines, while most N fertilization is produced using natural gas.

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Nitrogen fertilization has been extensively researched across the Cotton Belt (Boquet et al., 1993; Bondada et al., 1996; Boquet and Breitenbeck, 2000; Bondada and Oosterhuis, 2001; Boquet, 2005; Pettigrew and Adamczyk, 2006), but optimal rates remain a complex issue. This uncertainty in determining the optimal N fertilization rate for yield production under variable environmental conditions is due to the perennial indeterminate growth habit of cotton and the complexity of N cycling in the soil (Gerik et al., 1998).

Because N application should be based on realistic yield goals (McCarthy and Funderburk, 1990), field irrigation capability factors into N fertilization decisions. Although irrigation is incorporated into many Mid-South production systems, cotton economic yield improvements have proven inconsistent (Pringle and Martin, 2003). Field studies conducted under both arid climates (Turner et al., 1986; Ephrath et al., 1990, 1993) and temperature humid conditions (McMichael and Hesketh, 1982; Faver et al., 1996; Gerik et al., 1996; Pettigrew, 2004b) have shown that moisture deficit stress promotes reduced leaf area and stunted cotton growth. Lint yield is reduced because of reduced boll production, primarily because of increased boll abortions when the stress is extreme and occurring during reproductive growth (Grimes and Yamada, 1982; McMichael and Hesketh, 1982; Turner et al., 1986; Gerik et al., 1996; Pettigrew, 2004a).

Many of the effects from N deficiency on cotton growth mimic those of water deficit stress, such as reduced photosynthesis and leaf area development (Radin and Mauney, 1986). Many of the physiological interactions between water stress and N

Abbreviations: AFIS, advanced fiber information system; Chl, chlorophyll; DAP, days after planting; HVI, high volume instrument; LAI, leaf area index; PPFD, photosynthetic photon flux density; SLW, specific leaf weight.

deficiency have been previously documented (Radin and Parker, 1979a, 1979b; Radin and Ackerson, 1981; Radin, 1981; Radin et al., 1982). Of particular interest, is the finding that N deficient plants close their stomates at a higher leaf water potential than N sufficient plants (Radin and Parker, 1979b). However, most of this research was conducted on greenhouse or growth chamber plants grown in pots. Field plants often do not physiologically behave the same as pot grown plants due to the constrained root system (Carmi and Shalhevet, 1983). For instance, N deficiency decreased hydraulic conductance in pot grown cotton plants (Radin and Matthews, 1989). However, the reverse was observed in field grown plants where the hydraulic conductance increased as a result of N deficiency (Radin et al., 1991).

Elements of leaf Chl fluorescence estimate activities of some of the components of the light reaction of photosynthesis. The variable to maximal fluorescence ratio (Fv/Fm) is an estimate of the leaf's maximum quantum efficiency of photosystem II. Previous research has documented differences in chlorophyll fluorescence parameters between irrigated and dryland grown cotton plants (Pettigrew, 2004b). In addition, Baker and Rosenquist (2004) demonstrated that Chl fluorescence differences exist among N fertility levels for various crop species, but only when the stress has become severe for the Fv/Fm parameter. Because cotton crop photosynthesis underpins much of lint yield production (Pettigrew and Meredith, 1994) and Fv/Fm estimates the activity of an important aspect of photosynthesis, it would be important to further understand how water and N fertility stresses impact cotton leaf Chl Fv/Fm levels. In addition, it is not clear at this time whether the aforementioned interactions between N fertility levels and irrigation regimes for many physiological traits also are in play with the Chl Fv/Fm ratio in cotton plants.

The interactions between N and the soil moisture regime for cotton production remain complex and not clearly defined. Is additional N beneficial to cotton with irrigation? Can less N be utilized for dryland cotton? Therefore, the objectives of this research were to assess the growth and development, leaf Chl fluorescence Fv/Fm ratios, lint yield, yield component, and fiber quality differences between irrigated and dryland cotton when grown under three N fertility rates for a diverse group of four cotton cultivars.

MATERIALS AND METHODS

Field studies were conducted on two locations near Stoneville, MS, during the years 2009 to 2012. From 2009–2010, the study was conducted on a Dubbs silt loam soil (fine-silty, mixed, thermic Typic Hapludalf). In 2011 and 2012, the site was a Dundee silty clay loam soil (fine-silty, mixed, active, thermic Typic Endoaqualf). The treatments at both locations in this study consisted of two irrigation regimes, three N fertilization rates, and four cotton cultivars. The four cultivars were DP 0935B2RF, FM 840B2RF, Phy 485WRF, and ST 4554B2RF. These cultivars represented a range of maturities and breeding programs. Delta and Pine Land Co., Scott, MS, provided the seed of DP 0935B2RF. Seed of FM840B2RF and ST 4554B2RF were provided by Bayer CropScience, Research Triangle Park, NC. Dow AgroSciences-Phytogen Seed Company, Indianapolis, IN, provided the Phy 485WRF. These cultivars were treated with three rates of N fertilization (0 kg N ha^{-1}, 56 kg N ha^{-1}, and 112 kg N ha^{-1}). All three N fertilization rates were applied pre-plant as a urea-ammonium nitrate solution. The 112 kg N ha^{-1} rate of fertilization is a typical N rate for cotton grown in Mississippi (Oldham and Dodds, 2010). The plots were planted on 6 April in 2009, 31 March in 2010, 7 April in 2011, and 28 March in 2012. Plot size consisted of four rows spaced 1-m apart. Plot lengths were 18.3 m in 2009–2010 and 15.2 m in 2011–2012. Recommended insect and weed control measures were employed throughout each growing season as needed.

Half the plots were furrow irrigated and half the plots were grown dryland. One furrow irrigation occurred in 2009 (20 June), two applications occurred in both 2010 (21 June, 13 July) and 2011 (16 June, 11 July), and three applications occurred in 2012 (22 June, 5 July, 31 July). Approximately 2.54 cm of water was applied during each irrigation event. Tensiometers were used to monitor soil moisture at a 30-cm depth, with a goal of irrigations to be triggered when readings reached 40 to 50 centibars. However, this irrigation schedule was frequently adjusted (either accelerated or delayed) to accommodate the availability of the irrigation well among multiple users, required insecticide applications, and any restricted reentry intervals imposed from the insecticide usage.

A randomized complete block with a modified split plot treatment arrangement was the experimental design used for this research. Irrigation regimes were the main plots and the subplots were the cultivars and N rates arranged factorially. Irrigation regimes were randomly assigned and replicated in three blocks. In addition, within each of these blocks there were two replications containing each of the cultivar × N rate combinations, resulting in a total of six replications. The cultivar × N rate combination subplots were randomly assigned within each replication the first year of the study (2009). To minimize N treatment carryover effects from one year to the next, the subplots remained in their initial location the following year (2010). In 2011, the subplots were re-randomized within each replication due to the experiment being moved to a new location. Again, these subplots remained in their starting location the following year (2012).

Dry matter harvests were taken from one of the plot border rows each year approximately during the growth stage known as cutout [nodes above white bloom = 5 (Bourland et al., 1992)]. Cutout refers to a period of slowing vegetative growth and flowering due to a strong demand for assimilates by the existing boll load. These harvests occurred at 119 d after planting (DAP) in 2009; 124 DAP in 2010; 116 DAP in 2011; and 124 DAP in 2012. The above ground portions of plants from 0.3 m of row in one of the border rows were harvested for each plot. Height and the number of main stem nodes were determined for each plant and the plants were then separated into leaves, stems and petioles, squares, and blooms and bolls. Leaves were passed through a LI-COR 3100 leaf area meter (LI-COR, Lincoln, NE) to determine leaf area index. The various plant part samples were then dried for at least 48 h at 60°C, and dry weights were recorded. Dry weights and leaf area of the leaf sample were used to calculate specific leaf weights (SLW). Harvest index was calculated as the reproductive dry weight/total dry weight.

The percentage of incoming photosynthetic photon flux density (PPFD) intercepted by the cotton canopies was also quantified for each plot during the early squaring and cutout growth stages. By pairing simultaneous readings from a LI-COR LI

191SB line quantum sensor placed on the ground perpendicular to and centered on the row and also from a LI-COR LI 190SB point quantum sensor positioned above the canopy, we were able to determine the percentage intercepted PPFD. Two measurements were taken per plot with the means of those two measurements used for later statistical analyses. All measurements were collected between 1100 and 1500 h CDT with all the above canopy readings ≥1500 μmol m^{-2} s^{-1}.

Chlorophyll Fv/Fm ratios were taken on two leaves per plot using an OS1-FL Modulated Fluorometer (Opti-Sciences, Hudson, NH). Measurements were taken on the youngest fully expanded, disease-free, and fully sunlit leaves in each plot. These leaves were allowed to dark-adapt for at least 15 min before the Chl fluorescence measurements. To document alterations in Fv/Fm behavior at different times of the day, measurements were taken on the same leaves first before solar noon and then after solar noon. The two leaves measured before solar noon were tagged and then re-measured again after solar noon on the same day. These two measurements per plot were averaged together for both times of day and the means of those two measurements used for later statistical analyses. Measurements were collected from 119 to 123 DAP in 2009, 110 to 114 DAP in 2010, 102 to 106 DAP in 2011, and 112 to 117 DAP in 2012.

Two leaves, similar to those used for Chl Fv/Fm determinations, were collected per plot each year to determine the leaf Chl concentration. Two 0.4 cm^2 leaf disks were cut per leaf avoiding major veins (four total per plot) and were then placed in 10 mL of 950 mL L^{-1} ethanol. The Chl was extracted from these leaf disks over a 24-h period in darkness at 30°C. The Chl in the ethanol extract was then quantified spectrophotometrically according to the protocols described by Holden (1976). Measurements were collected from 119 to 123 DAP in 2009, 110 to 114 DAP in 2010, 102 to 106 DAP in 2011, and 112 to 117 DAP in 2012.

During approximately early to mid-September each year the cotton was defoliated using a two step process. The first step involved applying a mixture of 0.035 kg thidiazuron ha^{-1} and 0.0175 kg diuron ha^{-1} to the canopy. One week later a second treatment applied a mixture of 0.035 kg thidiazuron ha^{-1}, 0.0175 kg diuron ha^{-1}, and 1.68 kg ethephon ha^{-1} to complete the defoliation and also open most of the remaining unopened bolls. Defoliation was initiated when approximately 60% of the bolls had opened. Approximately 2 wk after defoliation, the center two rows of the plot were mechanically harvested with a spindle-picker equipped with an automated weighing system. Yield components were determined from a 50-boll sample that was hand-harvested after defoliation but before the mechanical harvest occurred. The 50 bolls were collected by picking all the bolls off of one plant before moving to the next adjacent plant and picking all its bolls. That process was continued until 50 bolls were picked. This technique ensures all boll positions were included in the sample, not just position one bolls.

These boll samples were subsequently ginned on a 10-saw laboratory gin, saving and weighing the lint and seed. Boll mass was calculated from the 50 boll samples by dividing the sample seed cotton weight by the number of bolls harvested. The lint percentage was determined from the ginned samples and then was used to calculate the total lint yield from the total of the mechanically harvested and hand harvested seed cotton. The boll mass and total seed cotton weights were used to calculate the number of bolls produced per area. Average seed mass was determined from 100 non-delinted seeds per sample and reported as weight per individual seed. Ginned lint from each plot was sent to Starlab Inc. (Knoxville, TN) for fiber quality determination. High volume instrument (HVI) was used to quantify staple length, length uniformity, fiber strength, fiber elongation, and fiber micronaire. A second lint sample was also tested for various fiber quality traits using the Advanced Fiber Information System (AFIS) (Zellweger Uster Inc., Knoxville, TN).

The two locations were statistically analyzed separately with analyses of variance (Proc Mixed; SAS Institute, 1996). Because the irrigation, N, and cultivar treatments returned to the same location for the second year at each location, year was considered a repeated measure sub-subunit in each analysis. Irrigation, N, and cultivars means were averaged across years and each other when statistical interactions were not detected. Means were separated by use of a protected LSD at $P \le 0.05$.

RESULTS AND DISCUSSION

Weather data during the 4 yr of this research indicate two dry years and two wet years for the experiment environments (Table 1). Year 2009 had an excessive amount of precipitation (22 cm) during the month of July, while 2012 had more than 10 cm of precipitation each month from June through August (encompassing the early squaring through boll setting periods). In contrast, 2010 and 2011 produced relatively dry periods from June through August with an accompanying high accumulation of thermal units. Consequently, 2010 and 2011 were extremely good years for testing the irrigation regime effects.

The treatment effects of both irrigation and N fertilization increased plant stature when the plants reached cutout at

Table 1. Monthly weather summary for 2009 to 2012 at Stoneville, MS.†

Month	2009	2010	2011	2012
	Precipitation, cm			
April	7.54	6.0	16.0	10.6
May	34.3	13.4	7.0	5.2
June	0.7	3.1	4.0	16.2
July	22.2	4.8	5.0	11.6
August	3.6	0.6	6.1	10.9
September	12.9	5.4	10.1	8.3
October	39.4	4.5	2.7	14.7
	Thermal units‡			
April	92	124	159	137
May	203	273	224	293
June	363	401	404	316
July	342	412	436	409
August	340	458	425	370
September	265	315	228	264
October	64	129	101	68
	Solar radiation, MJ m^{-2}			
April	602	–	626	638
May	547	681	748	688
June	759	743	743	751
July	663	710	723	700
August	656	667	689	634
September	442	609	530	528
October	317	566	523	462

† All observations made by NOAA, Mid-South Agric. Weather Service, and Delta Research and Extension Center Weather, Stoneville, MS.

‡ [(Max. temp + Min. temp.)/2] – 15.

both locations (Table 2). Cultivars did not interact with either irrigation or N fertilization and therefore, irrigation and N fertilization means were averaged across cultivars. Plants receiving irrigation were on average 16% taller, with 11% more nodes, 50% more leaf area, and 22% greater total dry weight than the non-irrigated plants. In contrast, the specific leaf weight (SLW) was decreased 19% from the irrigation. Both cellular and leaf area expansion is inhibited when the moisture supply is not sufficient causing a concentration of the cellular components over a reduced area and thus leading to a greater SLW. These irrigation growth responses were similar to those previously reported (Pettigrew, 2004b). Similar results for these growth traits were observed when N fertilization was applied. Plants receiving the highest rate of N fertilization were 17% taller, with 32% more leaf area index that intercepted 15% more of the incoming sunlight, and consequently produced 32% more total dry weight than the plants that did not receive N fertilization.

Behind these overall irrigation and N fertilization means were some statistically significant interactions between irrigation and N for these growth traits (Table 3). Briefly summarizing these interactions, sufficient N fertilization needs to be available to the plant to get the most growth benefits from an irrigation application. Similarly, there needs to be adequate soil moisture to maximize the growth stimulation provided by N fertilization.

Table 2. Cotton dry matter partitioning and canopy sunlight interception as affected by water regimes or N fertilization when grown at Stoneville, MS, during two periods (2009–2010) and (2011–2012).

Water regime	N fertility	Plant height	Main stem nodes	Leaf area index	Specific leaf weight	Total weight	Harvest index	Percent canopy interception
		cm	nodes plant^{-1}		—— g m^{-2} ——			%
				2009–2010				
Dryland		73.8	20.6	2.34	62.2	589.9	0.500	81.9
Irrigated		83.4	22.4	3.39	53.0	724.8	0.437	82.9
LSD 0.05		3.6	0.4	0.40	3.5	130.6	0.073 (ns)†	2.1 (ns)
	0 kg N ha^{-1}	72.1	20.9	2.51	59.1	568.5	0.464	76.5
	56 kg N ha^{-1}	77.2	21.1	2.58	58.0	616.1	0.472	81.5
	112 kg N ha^{-1}	86.5	22.4	3.50	55.6	787.5	0.469	89.3
	LSD 0.05	3.0	0.5	0.29	2.2	70.8	0.026 (ns)	2.5
				2011–2012				
Dryland		78.2	21.4	2.11	62.9	618.7	0.509	76.7
Irrigated		93.2	23.9	3.24	48.9	749.0	0.451	86.6
LSD 0.05		12.3	2.5 (ns)	0.72	1.6	67.6	0.147 (ns)	1.9
	0 kg N ha^{-1}	80.1	22.1	2.33	56.4	601.8	0.483	76.6
	56 kg N ha^{-1}	86.6	22.9	2.79	55.0	700.3	0.481	83.0
	112 kg N ha^{-1}	90.3	23.0	2.90	56.4	749.5	0.476	85.5
	LSD 0.05	3.5	0.5	0.34	2.0 (ns)	82.8	0.028 (ns)	2.3

† ns = not significantly different at the $P \leq 0.05$ level.

Table 3. Cotton dry matter partitioning and canopy sunlight interception as affected by interactions between water regimes and N fertilization rates when grown at Stoneville, MS, during two periods (2009–2010) and (2011–2012).

Water regime	N Fertility	Plant height	Main stem nodes	Leaf area index	Specific leaf weight	Total weight	Harvest index	Percent canopy interception
		cm	nodes plant^{-1}		—— g m^{-2} ——			%
				2009–2010				
Dryland	0 kg N ha^{-1}	69.2	20.2	2.16	63.0	520.8	0.487	77.5
	56 kg N ha^{-1}	73.3	20.5	2.19	62.9	555.4	0.500	80.8
	112 kg N ha^{-1}	79.0	21.1	2.66	60.6	693.6	0.514	87.4
Irrigated	0 kg N ha^{-1}	75.1	21.6	2.86	55.2	616.3	0.442	75.4
	56 kg N ha^{-1}	81.1	21.8	2.96	53.2	676.8	0.445	82.1
	112 kg N ha^{-1}	94.0	23.7	4.35	50.7	881.3	0.425	91.3
LSD 0.05†		4.6	0.7	0.46	3.6	123.4	0.058	3.6
	LSD 0.05‡	4.2	0.7	0.41	3.1	100.1	0.037 (ns)§	3.6
				2011–2012				
Dryland	0 kg N ha^{-1}	75.3	21.2	2.01	62.4	575.9	0.512	72.8
	56 kg N ha^{-1}	79.5	21.7	2.14	62.6	606.8	0.504	78.2
	112 kg N ha^{-1}	79.7	21.3	2.17	63.8	673.4	0.511	79.2
Irrigated	0 kg N ha^{-1}	85.0	23.0	2.66	50.5	627.7	0.454	80.3
	56 kg N ha^{-1}	93.7	24.1	3.44	47.4	793.8	0.458	87.8
	112 kg N ha^{-1}	100.8	24.7	3.63	49.0	825.5	0.441	91.7
LSD 0.05		9.0	1.1	0.56	2.8	117.1	0.120 (ns)	3.3
	LSD 0.05	5.0	0.7	0.48	2.8	117.1	0.039 (ns)	3.3

† For comparison of water regime means within an N fertility level.

‡ For comparison of N fertility means with a water regime.

§ ns = not significantly different at the $P \leq 0.05$ level.

The effect that irrigation and N fertilization had on Chl fluorescence (Fv/Fm) (an estimate of the maximum quantum efficiency for photosystem II) varied depending on the year (Table 4). In only one of the four study years did irrigation impact Fv/Fm (2009), and in that year the Fv/Fm for the irrigated plants was 1% lower than that exhibited by the dryland plants. Previous research (Pettigrew, 2004b) did not find statistically significant differences between irrigation regime main effects. In contrast, the Fv/Fm for the highest rate of N fertilization (112 kg N ha^{-1}) was 2% greater than the non-fertilized in 3 of the 4 yr.

Variation in Chl Fv/Fm was also found among cultivars and between the time of day when the measurements were collected (Table 4). In 2009 and 2012, FM 840B2RF exhibited a greater Fv/Fm than any of the other cultivars. Conversely in 2011 and 2012, Phy 485WRF produced a lower Fv/Fm than any of the other cultivars. FM 840B2RF is an okra-leaftype cultivar whereas the other cultivars are normal leaftype lines. Okra leaftype near isolines have previously been shown to exhibit greater Fv/Fm than their normal leaftype near isoline counterparts (Pettigrew, 2004b). The time of day also impacted Chl Fv/Fm readings as rates collected in the morning were 7% higher than those collected on the same leaves in the afternoon during 3 out of the 4 yr.

Irrigation regime impacted leaf chlorophyll concentrations, but that effect varied depending on the year (Table 5). During the 2 yr, 2009 and 2011, the dryland cotton had a leaf Chl concentration that was 20% greater than that observed in the irrigated plots. Greater SLW in the dryland plots suggests thicker

Table 4. Cotton leaf chlorophyll variable to maximal fluorescence ratio (Fv/Fm) as affected by water regimes, N fertilization, cultivars or the time of day the measurements were collected when grown at Stoneville, MS, during the years 2009 to 2012.

Water regime	N fertility	Cultivar	Time of day	2009 Fv/Fm	2010 Fv/Fm	2011 Fv/Fm	2012 Fv/Fm
Dryland				0.7526	0.7634	0.7885	0.7605
Irrigated				0.7485	0.7449	0.7928	0.7341
LSD 0.05				0.0040	0.0266 (ns)†	0.0166 (ns)	0.0520 (ns)
	0 kg N ha^{-1}			0.7433	0.7512	0.7909	0.7383
	56 kg N ha^{-1}			0.7500	0.7489	0.7866	0.7491
	112 kg N ha^{-1}			0.7583	0.7623	0.7943	0.7545
	LSD 0.05			0.0049	0.0088	0.0072 (ns)	0.0084
		DP 0935B2RF		0.7468	0.7502	0.8005	0.7494
		FM 840B2RF		0.7576	0.7679	0.7922	0.7552
		Phy 485WRF		0.7467	0.7487	0.7761	0.7356
		ST 4554B2RF		0.7510	0.7498	0.7938	0.7491
		LSD 0.05		0.0057	0.0102	0.0083	0.0097
			Morning	0.7757	0.7741	0.8070	0.7742
			Afternoon	0.7253	0.7342	0.7742	0.7199
			LSD 0.05	0.0242	0.0097	0.0398 (ns)	0.0530

† ns = not significantly different at the $P \leq 0.05$ level.

Table 5. Cotton leaf chlorophyll (Chl) concentration (conc.) and chlorophyll A/B ratio as affected by water regimes when grown at Stoneville, MS, during the years 2009 to 2012.

	2009		2010		2011		2012	
Water regime	Chlorophyll conc.	ChlA/B ratio	Chlorophyll conc.	ChlA/B ratio	Chlorophyll conc.	ChlA/B ratio	Chlorophyll conc.	ChlA/B ratio
	g m^{-2}		g m^{-2}		g m^{-2}		g m^{-2}	
Dryland	374	3.40	173	2.75	422	3.97	410	4.03
Irrigated	336	3.42	264	3.44	328	3.88	400	3.92
LSD 0.05	12	0.16 (ns)†	13	0.16	11	0.09	13 (ns)	0.10

† ns = not significantly different at the $P \leq 0.05$ level.

Table 6. Cotton leaf chlorophyll (Chl)) concentration (conc.) and chlorophyll A/B ratio as affected by cultivar or N fertilization rates when grown at Stoneville, MS, during two periods (2009–2010) and (2011–2012).

		2009–2010		2011–2012	
Cultivar	N Fertility	Chlorophyll conc.	ChlA/B ratio	Chlorophyll conc.	ChlA/B ratio
		g m^{-2}		g m^{-2}	
DP 0935B2RF		283	3.25	395	3.95
FM 840B2RF		297	3.32	408	3.83
Phy 485WRF		274	3.19	366	4.00
ST 4554B2RF		292	3.26	392	4.04
LSD 0.05		13	0.08	13	0.10
	0 kg N ha^{-1}	251	3.23	371	3.98
	56 kg N ha^{-1}	261	3.23	393	3.89
	112 kg N ha^{-1}	348	3.31	406	3.98
	LSD 0.05	11	0.07	11	0.09 (ns)†

† ns = not significantly different at the $P \leq 0.05$ level.

or denser leaves in the dryland cotton, which would support more Chl per unit leaf area (Pettigrew, 2004b). No differences were observed in 2012, but the reverse effect was observed in 2010 when leaves from the dryland cotton had 34% less Chl concentration than the irrigated. We were tardy getting the leaf samples collected in 2010. By the time we collected the samples, the dryland canopy leaves had already started the process of senescence where N was remobilized out of the leaves to support the developing boll load (Pettigrew et al., 2000). This phenomenon will explain the decreased leaf Chl concentration seen in the dryland leaves that year.

In addition to the irrigation effect, cultivar and N fertilization also impacted the leaf Chl concentration (Table 6). Averaged across years at both locations, FM 840B2RF had a greater leaf Chl concentration than the other cultivars while Phy 485WRF had the lowest. The higher leaf Chl for FM840B2RF matches the high Chl Fv/Fm also observed for this okra-leaftype cultivar. The highest rate of N fertilzaion (112 kg N ha^{-1}) had on average 24% greater leaf Chl concentration than the non-fertilized plots, with the 56 kg N ha^{-1} rate intermediate in value for leaf Chl. The N effect on leaf chlorophyll concentration is not surprising considering that N is a component of the Chl molecule.

The diversity of weather patterns seen among the years of this research (Table 1) produced a strong year × irrigation interaction for lint yield at both locations, therefore the yield and yield component data for the irrigation regimes were presented by years (Table 7). During the two dry years (2010 and 2011), irrigation increased lint yield production on average about 36%. Irrigation actually decreased yields 10% during one of the wet years (2009). Lygus bug (*Lygus lineolaris*) infestations were a major challenge

Table 7. Lint yield and yield components as affected by water regimes when grown at Stoneville, MS, during the years 2009 to 2012.

Water regime	Lint yield	Boll number	Boll mass	Lint percentage	Seed mass	Seed number	Lint index
	kg ha^{-1}	bolls m^{-2}	g boll^{-1}	%	mg seed^{-1}	seed boll^{-1}	mg seed^{-1}
			2009				
Dryland	1138	66	4.24	41.3	96	25.9	67.7
Irrigated	1013	62	4.02	40.8	94	25.2	65.2
LSD 0.05	98	10 (ns)	0.11	0.7 (ns)	2 (ns)	0.6	1.7
			2010				
Dryland	868	59	3.51	41.8	92	22.2	66.0
Irrigated	1208	74	3.86	42.4	97	23.0	71.3
LSD 0.05	98	10	0.11	0.7 (ns)	2	0.6	1.7
			2011				
Dryland	942	50	3.69	42.8	90	23.5	67.2
Irrigated	1254	65	3.96	41.0	91	25.7	63.2
LSD 0.05	264	17 (ns)	0.23	0.9	4 (ns)	1.3	4.1 (ns)
			2012				
Dryland	1003	49	4.17	41.2	96	25.4	67.5
Irrigated	824	42	3.96	41.2	94	24.9	65.5
LSD 0.05	339 (ns)†	23 (ns)	0.23 (ns)	0.9 (ns)	4 (ns)	1.3 (ns)	4.1 (ns)

† ns = not significantly different at the $P \leq 0.05$ level.

Table 8. Lint yield and yield components as affected by interactions between water regimes and N fertilization rates when grown at Stoneville, MS, during two periods (2009–2010) and (2011–2012).

Water regime	N fertility	Lint yield	Boll number	Boll mass	Lint percentage	Seed mass	Seed number	Lint index
		kg ha^{-1}	bolls m^{-2}	g boll^{-1}	%	mg seed^{-1}	seed boll^{-1}	mg seed^{-1}
			2009–2010					
Dryland	0 kg N ha^{-1}	870	56	3.67	41.8	91	23.5	65.4
	56 kg N ha^{-1}	990	59	4.00	41.8	95	24.5	68.2
	112 kg N ha^{-1}	1150	71	3.95	40.9	96	24.1	66.9
Irrigated	0 kg N ha^{-1}	855	55	3.71	42.3	92	23.2	67.8
	506kg N ha^{-1}	1097	67	3.91	42.0	95	23.9	69.0
	112 kg N ha^{-1}	1379	82	4.21	40.5	99	25.2	67.9
LSD 0.05†		102	7	0.13	0.8 (ns)	2	0.8	2.1
	LSD 0.05‡	74	4	0.13	0.6	2	0.8	1.9
			2011–2012					
Dryland	0 kg N ha^{-1}	913	47	3.82	42.4	93	23.7	68.3
	56 kg N ha^{-1}	1005	51	4.00	41.9	93	24.9	67.3
	112 kg N ha^{-1}	1000	51	3.98	41.7	93	24.9	66.4
Irrigated	0 kg N ha^{-1}	890	48	3.74	41.6	90	24.2	64.1
	56 kg N ha^{-1}	1077	55	3.98	41.1	93	25.2	64.9
	112 kg N ha^{-1}	1150	57	4.17	40.5	94	26.5	64.0
LSD 0.05		344 (ns)§	24 (ns)	0.23	0.9	4 (ns)	1.3	4.1
	LSD 0.05	69	4	0.14	0.5	2	0.9	1.9 (ns)

† For comparison of water regime means within an N fertility level.

‡ For comparison of N fertility means with a water regime.

§ ns = not significantly different at the $P \leq 0.05$ level.

Table 9. Cotton HVI fiber quality traits as affected by water regimes or N fertilization when grown at Stoneville, MS during two periods (2009–2010) and (2011–2012).

Water regime	N fertility	Fiber length	Length uniformity	Fiber strength	Fiber elongation	Fiber micronaire	Rd	+b
		cm	%	cN tex^{-1}	%			
			2009–2010					
Dryland		2.87	88.7	28.2	7.1	4.50	70.3	8.1
Irrigated		2.93	84.2	28.0	7.2	4.66	71.0	8.2
LSD 0.05		0.03	0.4	0.3 (ns)	0.2 (ns)	0.06	0.2	0.2 (ns)
	0 kg N ha^{-1}	2.89	83.8	27.8	7.1	4.63	70.5	8.0
	56 kg N ha^{-1}	2.90	84.1	28.2	7.2	4.63	70.5	8.1
	112 kg N ha^{-1}	2.91	84.0	28.2	7.2	4.48	70.9	8.4
	LSD 0.05	0.02 (ns)†	0.2 (ns)	0.3 (ns)	0.1	0.07	0.6 (ns)	0.2
			2011–2012					
Dryland		2.83	82.9	29.8	6.5	4.51	70.0	7.7
Irrigated		2.90	83.9	30.0	6.7	4.52	73.2	7.5
LSD 0.05		0.05	0.8	1.3 (ns)	0.2 (ns)	0.22 (ns)	1.5	0.8 (ns)
	0 kg N ha^{-1}	2.87	83.3	29.7	6.5	4.51	71.0	7.4
	56 kg N ha^{-1}	2.86	83.4	30.0	6.6	4.54	71.5	7.5
	112 kg N ha^{-1}	2.87	83.5	30.0	6.6	4.51	71.9	7.8
	LSD 0.05	0.02 (ns)	0.2 (ns)	0.4 (ns)	0.1 (ns)	0.10 (ns)	0.5	0.2

† ns = not significantly different at the P ≤ 0.05 level.

throughout much of the2012 growing season, which may have limited yield production and complicated the lint yield data for that year. Much of the irrigation increase observed during the two dry years was due to the production of more and larger bolls. These larger irrigated bolls also contained more seeds per boll than bolls from the dryland plants. These yield and yield component responses to irrigation during a dry year were similar to those reported earlier (Grimes and Yamada, 1982; McMichael and Hesketh, 1982; Turner et al., 1986; Gerik et al., 1996; Pettigrew, 2004a).

Similar to the response observed for many of the plant growth traits, a significant irrigation × N interaction was observed for lint yield (Table 8). At the first location (2009–2010), each increment of N fertilization increased lint yield an average of 140 kg ha^{-1} under dryland conditions. Under irrigated conditions, however, each increment of N increased yield by 262 kg ha^{-1}. Also, lint yield did not benefit from irrigation when no N fertilization had been applied. At the second location (2011–2012) there was not the increasing progressive response to N as was seen at the first location. This N response leveled off after the first 50 kg N ha^{-1}, with no response to the second increment of N under dryland conditions and a 60% reduction in the yield increase under irrigated conditions. Much of the irrigation × N interaction on lint yield came about because of its effect on the number of bolls produced per unit area.

Fiber quality traits were also impacted by irrigation and N fertilization (Table 9). The only consistent effect that irrigation had on HVI fiber quality traits were on fiber length and the Rd value for reflectance. Irrigation increased fiber length by 2% and Rd by 3% when averaged across locations. Averaged across both locations, the only fiber quality trait that N consistently affected was the +b value for yellowness. The fiber from the highest rate of N fertilization was 5% yellower than fiber from plots that did not receive N fertilization.

Behind the previously discussed significant irrigation effect on fiber length lurked a significant interaction between irrigation and N for fiber length that was consistent across both locations

Table 10. Cotton fiber length as affected by interactions between water regimes and N fertilization rates when grown at Stoneville, MS, during two periods (2009–2010) and (2011–2012).

Water regime	N fertility	2009–2010 Fiber length	2011–2012 Fiber length
		cm	
Dryland	0 kg N ha^{-1}	2.89	2.85
	56 kg N ha^{-1}	2.87	2.83
	112 kg N ha^{-1}	2.85	2.82
Irrigated	0 kg N ha^{-1}	2.90	2.90
	56 kg N ha^{-1}	2.93	2.90
	112 kg N ha^{-1}	2.96	2.92
LSD 0.05†		0.04	0.04
	LSD 0.05‡	0.03	0.02

† For comparison of water regime means within an N fertility level.
‡ For comparison of N fertility means with a water regime.

(Table 10). Nitrogen fertilization decreased fiber length 3% under dryland conditions. However, under irrigation the opposite trend was seen. Irrigated cotton fiber was 3% longer when N was applied. To our knowledge, this fiber length reversal interaction between irrigation regimes and N fertilization has not been reported before.

There were also some irrigation and N effects on AFIS fiber quality traits, although these tended to be inconsistent across the locations (Table 11). Irrigation decreased short fiber content by 15%, and this effect was consistent across both locations. Irrigation also decreased the number of fiber neps by 7%, but this effect was only observed at the first location (2009–2010). At the second location (2011–12), the irrigation application decreased the amount of seed coat neps by 19%. With exception of some minor reductions in fiber fineness (2%) and the fiber maturity ratio (1%) observed at the first location (2009–2010), N fertilization had essentially no effect on any of the AFIS fiber quality traits.

Most years, both irrigation and N fertilization are beneficial to cotton lint yield production. However the degree of the beneficial response from one of the components often

Table 11. Advanced Fiber Information System fiber quality traits as affected by water regimes or N fertilization when grown at Stoneville, MS, during two periods (2009–2010) and (2011).

Water regime	N fertility	Fiber neps	Seed coat neps	Short fiber content	Fiber fineness	Fiber maturity ratio
		—— no. g^{-1} ——		% weight	millitex	
			2009–2010			
Dryland		147	4.2	7.5	174	0.917
Irrigated		137	4.0	6.7	177	0.929
LSD 0.05		7	1.3 (ns)	0.3	1	0.005
	0 kg N ha^{-1}	141	4.1	7.2	177	0.928
	56 kg N ha^{-1}	139	4.4	6.9	176	0.926
	112 kg N ha^{-1}	146	3.9	7.7	174	0.916
	LSD 0.05	9 (ns)†	0.6 (ns)	0.4 (ns)	2	0.006
			2011			
Dryland		140	7.2	7.3	174	0.943
Irrigated		132	5.8	5.9	175	0.948
LSD 0.05		9 (ns)	1.2	0.3	4 (ns)	0.014 (ns)
	0 kg N ha^{-1}	141	6.9	6.8	174	0.943
	56 kg N ha^{-1}	132	6.0	6.6	174	0.946
	112 kg N ha^{-1}	133	6.6	6.6	175	0.947
	LSD 0.05	11 (ns)	1.2 (ns)	0.4 (ns)	2 (ns)	0.007 (ns)

† ns = not significantly different at the $P \leq 0.05$ level.

also depends on the level of the other component. These data provide a strong confirmation of Justus von Liebig's classic Law of the Minimum (Salisbury and Ross, 1978). Additional water or N did not produce additional benefits if the other was not in sufficient quantities so that it did not become a limiting factor. In this case, these effects were observed early on as the overall growth of the plant is compromised if either of these two components is at insufficient levels. Ultimately, this interrelationship between the N and water levels also manifest itself in the lint yield production.

This interaction between these two inputs initially manifested itself in alterations of the growth and development of the crop before finally impacting lint yield production. It provides both opportunities and challenges for Mid-South cotton producers. If circumstances prevent the application of the desired level for one of these inputs, should the same level of the second input be applied as originally planned or should that level be adjusted accordingly? If logistics preclude irrigation for a particular field, one might not want to apply as much N fertilizer as would be appropriate for an irrigated field. This approach reflects the philosophy of matching the level of N fertilization with the yield goal of a particular field (McCarthy and Funderburk, 1990). The tradeoff is that yield potential could be sacrificed during a wet year because the level of N applied might not have been sufficient to take advantage of the ample soil moisture. However, a foliar fertilization spray application might be able to salvage some of that yield potential for a lower fertilized field during a wet year. Similarly if circumstances prevent the application of all the planned N, it might not be worth it to turn on the irrigation pump as many times. The usage level of these costly inputs should be made on a field by field and year by year basis. This research provides information on what to expect in terms of plant growth and productivity from varying irrigation or N fertilization regimes when the other input is not available at optimal levels.

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